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Assessing the earthquake performance of existing buildings of various material types and configurations in New Zealand

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Abstract. The Initial Evaluation Procedure, conducted as part of Initial Seismic Assessment, is the main topic of this paper. An overview is provided of the eight key steps which define this procedure, and how they are used to determine ratio of New Building Standard (%NBS). The key steps are encapsulated in a programmed EXCEL worksheet (developed and current used in New Zealand) which takes into account various parameters and applies an algorithm to arrive at a preliminary assessed value. Actual examples of various buildings assessed using this procedure in recent years by authors are presented, and the results and some areas of interest are discussed.

1. Introduction

In the wake of the 2011 Canterbury earthquakes, assessing the structural performance of existing buildings has become a major focus for New Zealand structural engineers. To encourage consistency of evaluation, over the past few years the New Zealand Society for Earthquake Engineering, the Structural Engineering Society, the New Zealand Geotechnical Society, in conjunction with the Ministry of Business, Innovation and Employment, and the Earthquake Commission have developed a publication entitled “The Seismic Assessment of Existing Buildings, Technical Guidelines for Engineering Assessments”. This document sets out the requirements for structural engineers to follow when evaluating the earthquake performance for existing buildings. A two-stage evaluation process is recommended: (1) Initial Seismic Assessment ISA, “which enable a broad indication of the seismic rating of a building”, and (2) Detailed Seismic Assessment DSA, “which provide a more comprehensive assessment of the likely seismic rating of a building”. Both stages quantify seismic performance as a seismic rating expressed as a percentage standard achieved from application of the new building standards requirements (%NBS).

It must be underlined that there are major differences between the design and assessment processes. For the design of a new building, structural engineers are generally required to consider a single design imperative, typically the Ultimate Limit State, and to ensure that this building meets this minimum required standard for new buildings and therefore, the minimum acceptable performance assumed attained at any level of earthquake actions. A minimum earthquake standard for new buildings, with a well-defined use, is achieved by determining design actions for the required limit state, and applying these to a chosen structural system to determine the critical stresses that could possibly occur within the members. Appropriate design and detailing of the individual elements is then carried out in accordance with the respective material standards.Applying these steps from the traditional design process are not always valid when assessing an existing building, unless the behaviour of the existing structure remains predominantly elastic during a design level seismic event. Because this cannot always be assumed, the approach for seismic assessment must be different from the traditional design approach with the latter possibly leading to a result that can be “either excessively conservative or non-conservative” [1].

2. Seismic assessment of existing buildings

The scope of the SAEB guidelines is to assist all parties involved in buildings "life" to respond to challenges involved in understanding, managing and reducing seismic risk for people using these existing buildings. Having unique guidelines, engineers can assess the seismic behaviour of existing buildings and elements of these buildings, in similar way, and report the assessment results to building owners and organisations responsible for their management. The SAEB guidelines are for all types of existing buildings covering all eras and all types of construction materials. However, structures such as bridges, towers, masts, and retaining walls are excluded. These guidelines might be applied for buildings that undergo seismic retrofit, alteration or when a change of use is required.

The guidelines underline the expectations regarding the expertise of engineers who undertake seismic assessment of existing buildings:

- They must have relevant experience in structural design and evaluation of buildings for earthquake effects in order to exercise the degree of judgement required for this process. Therefore, every assessment shall be carried out by or under the direction of a New Zealand Charter Professional Engineer (CPEng).
- They must have specific training in the objectives of and processes involved in the assessment procedures in order to provide consistent reporting; template covering letter and engineering assessment summary report are available.

2.1. Initial Seismic Assessment

Initial Seismic Assessment (ISA) is the first recommended step of seismic assessment of any existing building and is considered an important "first look" at the building performance. ISA is a "qualitative procedure that involves observing building attributes, and then using these to develop a holistic understanding of how the building will respond to an earthquake. It provides an initial assessment of its earthquake rating" [2]. Depending on the purpose of ISA and the time when the building was erected, this could involve:

- Basic ISA which will involve collecting basic building information, provided usually by local council, an exterior inspection, and completing an Initial Evaluation Procedure (IEP).
- Comprehensive ISA, which in addition to the above-mentioned information will require an interior inspection, available structural drawings (i.e. foundations, stairs, columns, walls, floors) review and if necessary supplementary calculations. Comprehensive ISA is recommended especially "if building's earthquake rating is around the threshold levels of 34%NBS and 67%NBS" [2].

The report with the results of the ISA would be appropriate for certain situations and can include information such as: building structural system description, the level of the information available at the time when the report was produced, limitations of the process and the results of the IEP.

IEP is a fundamental part of ISA and consists in "making an initial assessment of the standard achieved for an existing building against the minimum life safety standard required for a new building (the percentage of new building standard, or %NBS)" [2]. More details and examples of IEP produced by the authors, for buildings made of different types of materials and erected at different time, will be presented in this paper.

2.2. Detailed Seismic Assessment

Despite of the fact that there is no prerequisite for buildings to have an ISA before proceeding to DSA, it is strongly encouraged that engineers develop first a qualitative procedure (ISA) in order "to gain a holistic view of the building's potential structural weaknesses" [3].

Detailed Seismic Assessment (DSA) is "a quantitative procedure" used to confirm an earthquake rating for an existing building, "to identify retrofit needs and provide a benchmark for proposed upgrading strategy to be tasted against" [3]. Understanding the behaviour of structural systems and the likely behaviour of buildings in earthquakes must be done by quantifying the strength and deformation capacities of existing building and by checking the building's structural integrity against the actual loads/deformations.

Depending on the circumstances and stated objective (client requirements) the approach taken to carry out a DSA may have considerable differences depending on the actual condition of building. Some buildings will require the use of lengthy and detailed analyses, some will not. For buildings with visible structural problems it will be better for the time to be spent in completing an appropriate solution for retrofit, rather than gaining a detailed understanding on how the existing structure might perform.

The objectives for the DSA recommended by NZ Technical Guidelines for Engineering Assessments are to [3]:

- Assess the level of earthquake shaking at which the ultimate capacity (seismic) is reached and identify the point at which the conditions are met for a significant life safety hazard.
- Determine an earthquake rating for the investigated building in terms of %NSB that is more reliable than the rating from ISA.
- Provide details on the expected mode of failure to assist territorial authorities to make decisions on life safety issues to determine earthquake prone building status.
- Determine whether or not a building is an earthquake risk building (i.e. < 67%NBS).
- Provide guidance on the likely needs for retrofit.

3. Initial Evaluation Procedure

As mentioned above IEP is an integral part of ISA, and it was designed to accommodate a varying level of information about structural characteristics regarding the building under investigation. It involves making an initial assessment of the standard achieved for an existing building against the minimum life safety standard required for a new building (the percentage of new building standard, or %NBS) [1].

With as few resources as possible, the IEP will identify, to an acceptable level of confidence, most of those buildings that fall under the earthquake-prone building threshold. As some of these aspects are unknown to the engineer, when the IEP is completed for the first time, it is a good practice for this process to be repeated when new information regarding the investigated building becomes available; information which results in any changes to the original IEP must be recorded so it can be referred to by anyone considering or reviewing the results. An outline of the IEP procedure is shown in figure 1 [2].

There is a standard form used for the IEP procedure and this has eight steps as follows:

- General Information: photos of the building exterior, building plans, list of relevant features, notes on any building strengthening work, recording the characteristics of any adjacent buildings, noting all information sources to complete the assessment.
- Determine Baseline Percentage of New Building Standard for each orthogonal direction as a product of: nominal %NBS, near fault scaling factor (factor E), hazard scaling factor (factor F), return period scaling factor (factor G), ductility scaling factor (factor H), structural performance scaling factor (factor I).
- Assessment of Performance Achievement Ratio (PAR) for longitudinal and transverse directions as a product of factors: plan irregularity (factor A), vertical irregularity (factor B).
- Short columns (factor C), pounding potential (factor D), site characteristics (factor E), other factors (factor F).
- Percentage of New Building Standard (%NBS) – Seismic Rating: the lower value obtained for longitudinal and transverse directions.
- Earthquake-prone: is %NBS < 34?
- Potential Earthquake Risk; is %NBS < 67?
- Provisional Grading for Seismic Risk based on IEP.

- Identification of Potential Sever Structural Weaknesses (SSWs) that could result in significant risk to a significant number of occupants: number of storeys above ground, presence of heavy concrete floors and/or roof.

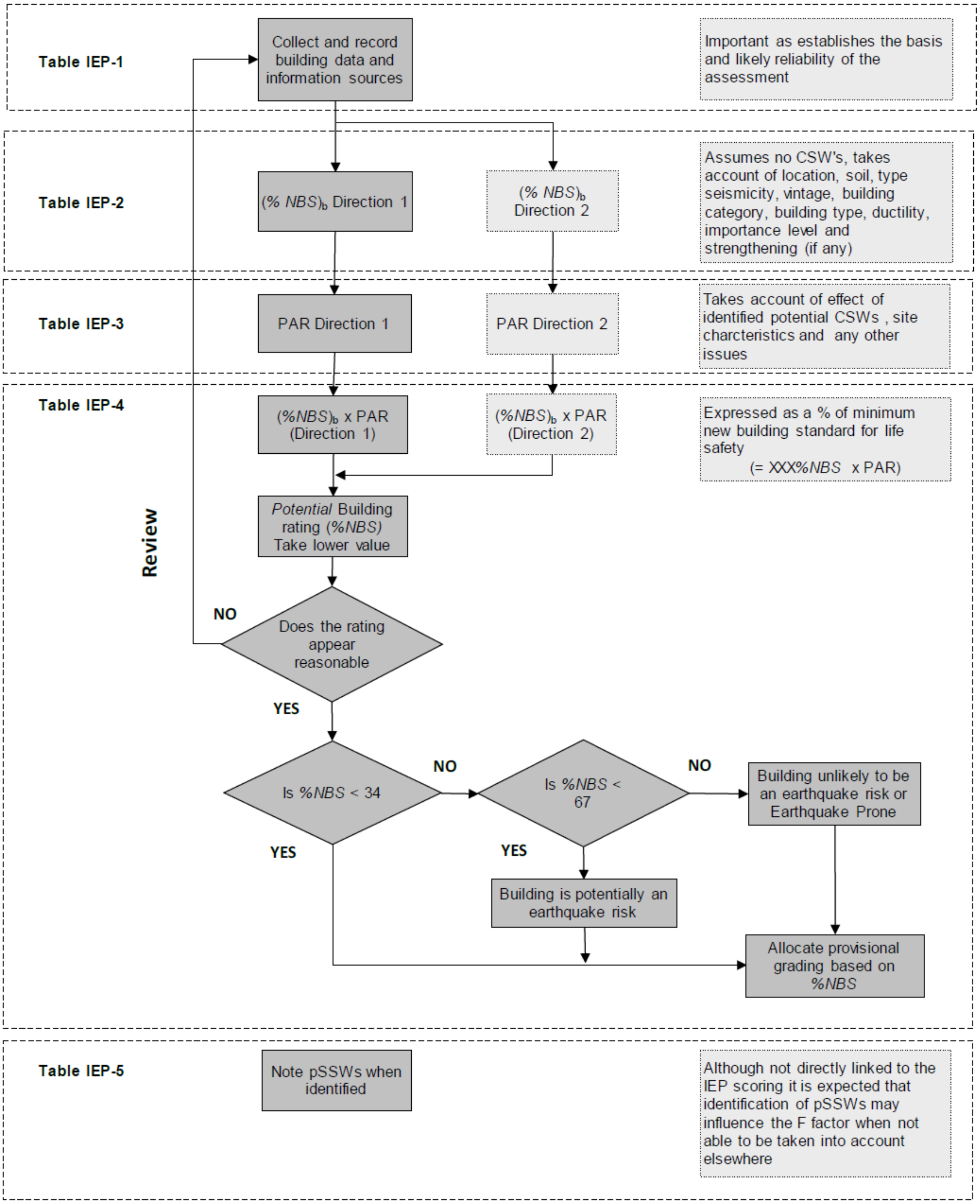

Figure 1. Initial Evaluation Procedure [2].

The IEP is a largely qualitative, score-based assessment based on the current standard for earthquake actions for new buildings in New Zealand, NZS 1170.5.2004. It is based on generic building characteristics and is dependent upon knowledge available at the time of the assessment. Due to its qualitative nature it should not come as a surprise that an IEP procedure of the same building carried out by two or more experienced engineers may have different results; this is acceptable, especially if the level of available information was different. If differences in opinion regarding the IEP results (from ISA) cannot be settle through professional discussion, the guidelines recommend being resolution by completion of a DSA [2].

4. Case study: Reinforced concrete building

The first publication on earthquake design was written by C. Reginald Ford, in 1926, a few years before the 7.8 magnitude earthquake (Napier 1931) that resulted in significant changes to New Zealand construction practice. After the devastating earthquake in Napier, a Building Committee was set up and a draft earthquake building by-law was presented to the NZ Parliament in 1931. This ended up being published by NZ Standards as the 1935 New Zealand Standard Model Building By-Law (NZSS 95:1935) and the 1939 NZS Code of Building By-Laws (NZSS 95:1939) [4].

The 1955 revision of NZS Standard Model Building By-Law (NZSS 95:1955) introduced changes but lacked improvement in seismic structural design. The NZS 1900:1964 code was a significant evolution from the previous one; it was based on knowledge from the American codes, ACI318-63, 1963 and the European codes, CEB-1964, 1964. NZS 3101:1982 provided improvement requirements in the detailing of plastic regions, including shear, confinement and anti-buckling reinforcement. This was reviewed and updated in 1995 and 2006 to incorporate further knowledge from research and the revision of earthquake actions standard NZS 1170.5:2004 [4].

Seismic assessments for existing buildings are done assuming that all buildings have been designed and built in accordance with buildings standards current at that time and with good practice. The changes which have occurred within the New Zealand standards have been taking into account within the IEP working spreadsheet; this includes information tables and required figures for assessment.

4.1. General information about building

A multi-storey reinforced concrete building situated in the Auckland Central Business District (CBD), was designed and built around 1999 on top of the previous building with two level reinforced concrete frame car park. The building has six levels between axis C09 and C22 and two levels between axis C02 and C09. The structural system is comprised of reinforced concrete frames (columns and beams) and prestressed precast floor elements (Hollow Core). The roof consists of lightweight metal cladding on purlins over structural steel.

Information sources were visual inspection of the exterior and interior of the building, and Auckland Council files for property and geotechnical report. The report was completed for a private company interested in buying some space in this property.

4.2. Results from IEP

Introducing all information regarding this building on the standard IEP working spreadsheet the following results were obtained:

- Nominal %NBS: for both longitudinal and transverse directions $(\%NBS)_{nom}$ = 28%: taking into account near fault, hazard, return period, ductility and structural performance scaling factors.
- Baseline %NBS for building: for both directions $(\%NBS)_b$ = 152%: taking into account near fault, hazard, return period, ductility and structural performance scaling factors.
- Performance Achievement Ratio: for both directions PAR = 0.59: taking into account plan and vertical irregularity, short columns and pounding effects, site characteristics and other factors for allowance of all other characteristics of the building.

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- Percentage New Building standard or seismic rating based on the above factors: %NBS = 90%.
- Provisional Grading for Seismic Risk based on IEP: Seismic Grade A - seismic grading from IEP should be considered provisional and subject to confirmation by detailed assessment.

As the building was design and constructed around 1999, the results from IEP are closed with what shall be expected.

5. Case study: Unreinforced masonry building

Most of New Zealand's URM buildings were built between the late 1870s and 1940, and the construction methods are relatively uniform with only a few variations [5]. Foundations were typically shallow strip footings: often thin and unreinforced for small buildings and deeper and nominally reinforced with plain reinforcing bars, flats or train/tram rails. The commonly used nominal thickness of brick walls in New Zealand are 230 mm (two wythes), 350 mm (three wythes) and 450 mm (four wythes). This is in addition to any outer veneer of 110 mm (one wythe). Common types for walls were [6]:

- Solid walls - used generally for industrial buildings and buildings on the outskirts of town, and for partition walls and walls in lower storeys that are not visible.
- Cavity walls – used in buildings to control moisture ingress.

Unreinforced masonry (URM) building can be vulnerable to earthquake actions because of their high centre of mass, lack of integrity between elements and lack of deformation capacity. Assessing the performance of these buildings can be complex as the mechanism of failure is different from those occurring in other buildings types [6]. For URM buildings built prior to 1935, Steps 2 to Step 4 of IEP can be carried out using the attribute scoring method. The %NBS is determined directly from the total assessed score for each of the eight items: structural continuity, configuration, condition of structure, wall (URM) proportions, diaphragms, engineering connections between floor/roof diaphragms and walls, and walls and diaphragms capable of spanning between, foundations and separation from neighbouring buildings [2].

5.1. General information about building

The building is constructed of URM around 1930, generally up to 300 mm thick around the exterior, and comprising 200 mm thick walls with 100 mm thick leaf fixed as cladding with an air gap between. The building is placed on a significant slope from the road down to the rear, dropping by a building storey in height (i.e. two storeys at the street and three storeys at the rear). The building comprises five separate units with an URM full height internal wall approximately 200 mm thick separating them. The roof is of timber construction with lightweight metal cladding. The floors are typical tongue and groove floor boards on timber joists. From the original drawings the internal foundations appear to step down the slope from the road; these comprise URM piles on concrete pads. The exterior perimeter foundations are URM foundation walls on concrete strip footings.

From a visual perspective the property appears to be constructed as one building. However, from our inspection and the data provided in council files there are four units constructed around 1930 and a unit constructed later (unknown date).

5.2. Results from IEP

Introducing all information regarding this building on the standard IEP working spreadsheet the following results were obtained:

- Nominal %NBS: for both longitudinal and transverse directions $(\%NBS)_{nom}$ = 2.90%.
- Baseline %NBS for building: for both directions $(\%NBS)_b$ = 28%.
- Performance Achievement Ratio: for both directions PAR = 1.0.
- Percentage New Building Standard: %NBS = 28%.
- Provisional Grading for Seismic Risk based on IEP: Seismic Grade D.

Using attribute scoring method, the following results were obtained:

- Percentage New Building Standard: %NBS = 23%.
- Provisional Grading for Seismic Risk based on IEP: Seismic Grade D

The building was designed and constructed around 1930, with multiple cracks in the walls noted, and an approximate 800 mm high parapet: the results using the IEP procedure and scoring methods are close with what would be expected. While there is a difference between results for the %NBS, the results for seismic grade are the same.

6. Case study: Timber buildings

In New Zealand timber is a readily available material and it has been used widely for many building types since the earliest European settlement. The two main categories of timber buildings are [7]

- Timber framed structures such as those designed using non-specific design guides and standards.
- Engineered buildings as halls, commercial and industrial buildings.

Timber has been used as well in other buildings types that are primarily constructed of other materials – with timber used for roof framing, floor joists, flooring and sarking under roofs etc.

It has been known that timber framed, residential and small commercial, buildings generally perform well in earthquakes, and the 2010/2011 Christchurch earthquake confirmed this. Timber framed structures, known as stick framing, are made of small sections timber such as 45 x 90 mm that combined with timber studs create wall frames. These are equipped with top and bottom plates.

Before the introduction of NZS 3604:1978 bracing was commonly provided by addition of let-in diagonal braces or cut-in diagonal braces between studs. Some older buildings with timber framed walls rely on an internal lathe and plaster lining to provide the bracing instead of employing diagonal members; this construction system was used in the building for which IEP is presented in this paper. Modern timber framed walls are likely to be reliant on their lining materials for providing bracing resistance. Plasterboard, plywood, particle board and sometimes fibre cement are linings used now.

6.1. General information about building

The example we refer to is a two storey timber building in Wellington, with a steep heavy tiled roof and timber and concrete partial basement. From information provided by the Wellington City Council Archives, the original property/dwelling was constructed in 1893. Major alterations to the dwelling are recorded as being completed in 1927. The exterior walls cladding is a type of weatherboard and the interior walls are of particleboard. In 1953 several structural walls were demolished with an adverse impact on building bracing capacity. At the time of inspection some of the walls were found in poor condition and water infiltration and damage on the second story ceiling were observed.

In 1959/1960 parts of the building were demolished during the construction of an adjacent reinforced concrete building. The actual layout is different from the one presented on the initial plan.

6.2. Results from IEP

Introducing all information regarding this building on the standard IEP working spreadsheet the following results were obtained:

- Nominal %NBS: for both longitudinal and transverse directions $(\%NBS)_{nom}$ = 3.63%.
- Baseline %NBS for building: for both directions $(\%NBS)_b$ = 20%.
- Performance Achievement Ratio: for both directions PAR = 1.05.
- Percentage New Building Standard: %NBS = 21%.
- Provisional Grading for Seismic Risk based on IEP: Seismic Grade D

For this building the owner was proceeding with a request for DSA. The required calculations for DSA were done for the structural timber elements. More than half of the structural walls were found with inadequate bracing; this was mainly because of the removal of some of the structural walls during a building alteration carried out in 1953.

The building was found to have an unsatisfactory seismic protection level, achieving a lowest 25 NBS% for the ground floor on the transversal direction, and 36 NBS% for the ground floor on the longitudinal direction.
The recommendations for this property taking into account the DSA results, the age, the structural system and the usage of the building, was to carry out seismic strengthening remedial works in order to address deficiencies that were found. These would address:

- Inadequate bracing units required for earthquake.
- Inadequate connection of the subfloor framing with foundation.
- Damages to external building walls to avoid future deterioration of structural elements.

7. References

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